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J. L. Klay

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Jennifer L. Klay

Lawrence Livermore National Laboratory, Livermore, California, U.S.A. 94550

E-mail: `klay@llnl.gov`

Abstract. A strategy to study flavor-dependent parton energy loss by tagging heavy quark jets in p+p, p+Pb and Pb+Pb collisions at the LHC is discussed. Estimates for production cross-sections and experimental techniques employed at collider detectors to search for $Q\overline{Q}$ jets are presented and a brief evaluation of the capabilities of CMS, ALICE and ATLAS detectors are given.

1. Introduction

Evidence for the hard-scattering of partons and their subsequent fragmentation into jets of hadrons have been observed in nuclear collisions for the first time at RHIC [1]. These hard probes, which are formed early in the collision, interact strongly with the hot, dense medium. Significant (factor ∼5) suppression of the leading hadron transverse momentum spectra [2, 3] and the shrinking away-side two-particle leading hadron correlations [3, 4] in central Au+Au but not d+Au collisions have been used to estimate that energy densities 15-100 times larger than cold nuclear matter are generated at RHIC [5].

While jet production cross-sections at RHIC are sufficient to produce jets with $E_T \sim$10-30 GeV, and their modifications can be observed via indirect observables, at LHC jets will be measured and studied directly. The factor 30 increase in center of mass energy brings a factor $\sim 10^3 - 10^4$ increase in the partonic hard-scattering cross-sections [6] and 1-2 orders of magnitude increase in the heavy quark pair production cross-sections at LHC compared to RHIC [7].

As with light quarks and gluons, heavy quarks will interact strongly with the medium and lose energy via induced gluon radiation [8]. Since soft gluons radiated at small angles have very large formation times, their emission has been shown to be suppressed for angles $\theta < m_q/E$. For heavy quarks, the magnitude of this "dead-cone" effect [9] is substantial and depends on the density and lifetime of the medium. For conditions expected at the LHC, heavy quarks will radiate 1/4 to 1/2 as much energy as light quarks. This may be measurable by experimentally isolating heavy flavor jets in p+p, p+Pb and Pb+Pb collisions.

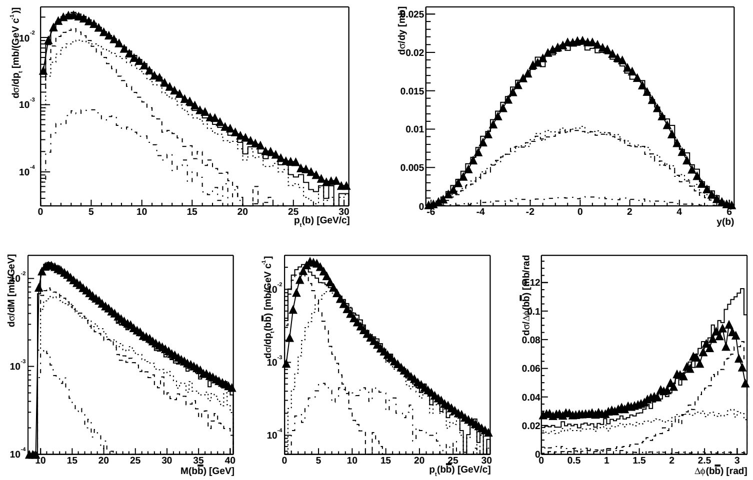

Figure 1. Beauty production in PYTHIA (solid histogram - total, dashed - leading order pair creation, dotted - flavor excitation, dot-dashed - gluon splitting) compared to a NLO calculation (triangles), from the CERN Yellow Report on heavy flavor production at the LHC, Ref. [10].

2. Heavy flavor production at LHC

Per Pb+Pb event at $\sqrt{s_{\rm NN}}$= 5.5 TeV, $\sim$250 $c\overline{c}$ and $\sim$7 $b\overline{b}$ pairs are expected, compared with $\sim$10 $c\overline{c}$ and $\sim$0.05 $b\overline{b}$ per Au+Au collision at 200 GeV [10]. Within Monte-Carlo event generators such as PYTHIA, the leading order perturbative QCD $2 \rightarrow 2$ scattering process is labeled “pair creation”, and next-to-leading order (NLO) terms, which contribute significantly to the total cross-section, are included via the processes “flavor excitation” and “gluon splitting” [7]. Flavor excitation describes the excitation of a Q or $\overline{Q}$ out of the initial state into the final state while gluon splitting represents pair production during the parton shower after hard-scattering of a light quark or gluon. Fig.1 shows the differential production of $b\overline{b}$ pairs for each of these mechanisms in PYTHIA‡ for a given set of input parameters, compared to an NLO calculation as a function of single quark p_T rapidity, pair invariant mass, pair p_T and relative pair azimuthal angle. In contrast to the nearly flat distribution of flavor excitation and gluon splitting pairs in $\Delta\phi$, the leading order pairs are emitted nearly back-to-back§.

3. B-Tagging in Collider Detectors

Measurements of the total cross-section for $b\overline{b}$ and $t\overline{t}$ production and searches for super-symmetric particles and the Higgs boson ($H \rightarrow b\overline{b}$) rely on good identification of b-jets. The $\approx$17% semi-leptonic decay branching ratio of B-mesons and the strong back-to-back correlation of leading order $b\overline{b}$ pairs can be used to experimentally select b-jets. CDF

‡ Selecting MSEL(4) or MSEL(5) in PYTHIA generates only leading order pairs. One must use MSEL(1) and select events with $Q\overline{Q}$ pairs in order to study flavor excitation and gluon splitting.

§ A similar study with other Monte-Carlo generators such as HERWIG and ISAJET has also been performed for $p+\overline{p}$ collisions at the $\sqrt{s}$=1.8 TeV [11].

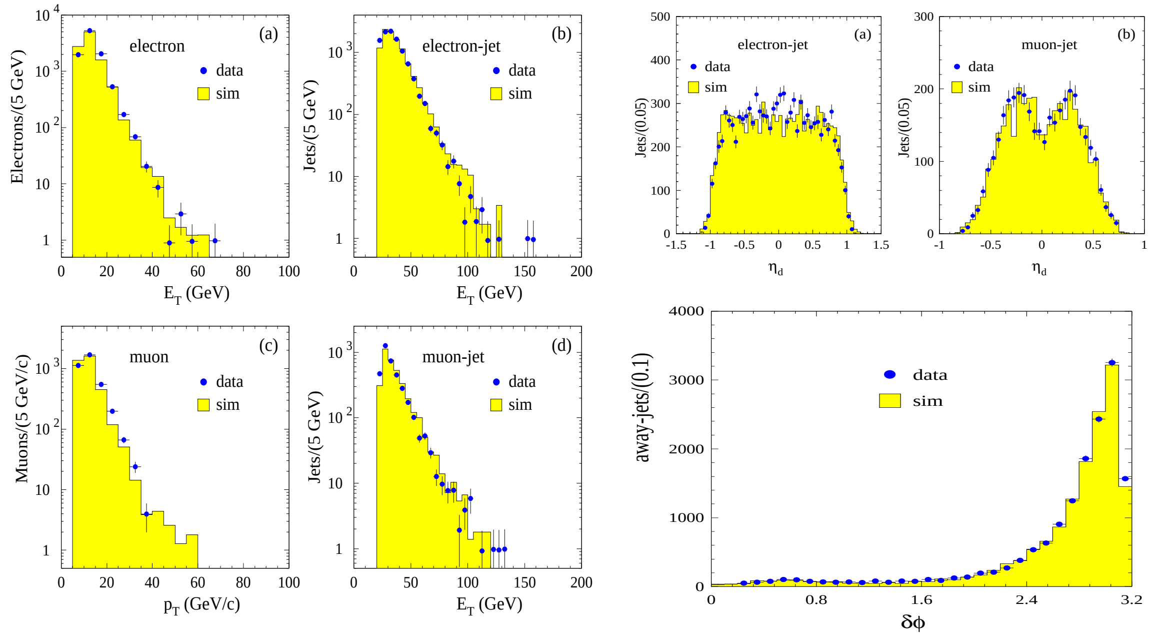

Figure 2. Lepton-tagged jets measured by CDF in $p+\overline{p}$ collisions at $\sqrt{s}$= 1.8 TeV compared to a simulation of heavy flavor jets produced in HERWIG from Ref. [13].

and D0 at the Tevatron and CMS and ATLAS at LHC have developed several "b-tagging" algorithms which (1) identify jets(di-jets) containing tracks from a displaced secondary vertex, (2) identify jets(di-jets) containing leptons within a narrow radius around the jet axis and (3) combine both of these features ("superjets") [13].

Some experimental results on b-tagging in $p+\overline{p}$ collisions at 1.8 TeV from CDF are shown in Fig.2. The p_T spectra of electrons and muons and their parent jets for events in which a lepton with E_T>8 GeV is found and a di-jet with measured (uncorrected) $E_T > 15 GeV$ is reconstructed are shown on the left. The right upper panel shows the pseudorapidity distributions of the tagged jets, while the lower right panel shows the azimuthal correlation between near and away b-tagged di-jets. The data have been corrected for fake lepton tags and are compared to a tuned HERWIG simulation of $b\overline{b}$ production [13].

4. Evaluation of CMS, ALICE and ATLAS for b-tagging

The key detector capabilities needed for efficient, reliable b-tagging in heavy ion collisions are (1) good jet reconstruction in heavy ion collisions (with a reasonable handle on the large soft background) over full azimuth (2) fine spatial resolution for displaced vertex reconstruction (3) lepton identification and triggering (4) charged particle tracking for jet shape (j_T, j_L) and fragmentation studies. Table 1 lists some of the relevant parameters associated with each of the three LHC detectors interested in heavy ion collisions. ALICE has smaller acceptance, but the jet rates at LHC are large and should be sufficient for a robust jet physics program in ALICE [6]. While CMS and ATLAS have high granularity electromagnetic and hadronic calorimeters which provide better jet energy resolution, essential for reconstructing di-jet

Table 1. Comparison of detector parameters relevant for b-tagging in Pb+Pb collisions at LHC, from Refs. [6, 10, 12, 14, 15].

	ALICE	CMS	ATLAS
Jet $\Delta E/E$ in Pb+Pb (dN/dy $\approx$5000)	39% (50 GeV) 31% (100 GeV)	20% (50 GeV) 16% (100 GeV)	18% (50 GeV) 11% (100 GeV)
Secondary vertex resolution	60μm (1 GeV/c) 20μm (10 GeV/c)	100-200μm (1 GeV/c) 20-40μm (10 GeV/c)	100-200μm (1 GeV/c) 15-35μm (20 GeV/c)
Lepton id (mid-rapidity)	$e^{\pm}$ (p_T>1 GeV/c)	$e^{\pm}$ (p_T>1 GeV/c) $\mu^{\pm}$ (p_T>3.5 GeV/c)	$e^{\pm}$ (p_T>2 GeV/c) $\mu^{\pm}$ (p_T>3 GeV/c)
Charged tracking acceptance resolution, $\Delta p/p$ efficiency, ε	p_T>100 MeV/c ($\lvert\eta\rvert < 0.9$) 9% (100 GeV/c) 99%	p_T>1 GeV/c ($\lvert\eta\rvert < 2.4$) 1.5% (100 GeV/c) 80%	p_T>1 GeV/c ($\lvert\eta\rvert < 2.7$) 3% (100 GeV/c) 70%

invariant mass, ALICE has the advantage in charged particle tracking with high efficiency and broader p_T acceptance, more important for studying jet fragmentation. Charged particles alone can and will be used for jet reconstruction in ALICE. The addition of a proposed electromagnetic calorimeter improves the energy resolution over limited acceptance ($\Delta\phi < 2\pi/3$)||. All three detectors achieve excellent position resolution in their silicon tracking systems for reconstructing displaced vertices and good mid-rapidity lepton identification, either through $e^{\pm}$ in calorimeters (all three) or $\mu^{\pm}$ in muon spectrometers (CMS, ATLAS).

A preliminary study of b-tagging via dislocated vertex has already been undertaken in ATLAS [15]. For E_T=100 GeV jets and a tagging efficiency of 50%, the rejection power for misidentified light-quark jets is ∼30 in Pb+Pb compared to ∼300 in p+p. Re-tuning of the software for the higher backgrounds in Pb+Pb and incorporating soft muon tagging should improve this result and will be studied.

5. Conclusion

Large jet and heavy quark production rates make b-tagging an attractive observable for studying the flavor dependence of partonic energy loss at the LHC. A comprehensive study, comparing the shapes and composition of b-tagged jets with an untagged sample in p+p, p+Pb and Pb+Pb collisions will provide new insight into the properties of nuclear matter in extremis. The design of the three large detectors ALICE, CMS and ATLAS make them well-suited for this measurement with overlapping, complementary strengths and weaknesses. More detailed simulations of each detector and tagging algorithm using Pb+Pb events will help to refine this comparison and to prepare for first collisions.

|| Reported ALICE jet energy resolution includes the proposed EMCalorimeter [12]

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